



# *U.S. Army's Ground Vehicle Energy Storage*



**TECHNOLOGY DRIVEN. WARFIGHTER FOCUSED.**

**Sonya Zanardelli & Dr. Laurence Toomey**

Energy Storage Team, US Army TARDEC

[sonya.zanardelli.civ@mail.mil](mailto:sonya.zanardelli.civ@mail.mil) 586-282-5503

April 16, 2013

Report Documentation Page				Form Approved OMB No. 0704-0188	
Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.					
1. REPORT DATE <b>09 APR 2012</b>		2. REPORT TYPE <b>Briefing Charts</b>		3. DATES COVERED <b>15-03-2012 to 03-04-2012</b>	
4. TITLE AND SUBTITLE <b>U.S. Army's Ground Vehicle Energy Storage</b>				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S) <b>Sonya Zanardelli; Laurence Toomey</b>				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) <b>U.S. Army TARDEC, 6501 East Eleven Mile Rd, Warren, Mi, 48397-5000</b>				8. PERFORMING ORGANIZATION REPORT NUMBER <b>#23783</b>	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) <b>U.S. Army TARDEC, 6501 East Eleven Mile Rd, Warren, Mi, 48397-5000</b>				10. SPONSOR/MONITOR'S ACRONYM(S) <b>TARDEC</b>	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S) <b>#23783</b>	
12. DISTRIBUTION/AVAILABILITY STATEMENT <b>Approved for public release; distribution unlimited</b>					
13. SUPPLEMENTARY NOTES <b>briefing charts for HTUF military truck action group 2013</b>					
14. ABSTRACT <b>- TARDEC Energy Storage Team Goals, Mission, &amp; Role - Army Applications &amp; Challenges - Ragone Plot - Commercial vs Military - Dual Use 6T Program</b>					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT <b>Public Release</b>	18. NUMBER OF PAGES <b>23</b>	19a. NAME OF RESPONSIBLE PERSON
a. REPORT <b>unclassified</b>	b. ABSTRACT <b>unclassified</b>	c. THIS PAGE <b>unclassified</b>			

- **TARDEC Energy Storage Team Goals, Mission, & Role**
- **Army Applications & Challenges**
- **Ragone Plot**
- **Commercial vs Military**
- **Dual Use 6T Program**



## Energy Storage Goals

- Develop **safe, reliable and cost** effective energy storage systems
- Reduce **battery weight & volume burden** (Increase Energy & Power Density)
- Reduce logistics and fuel burdens
- Extend **calendar and cycle life**

## Energy Storage Mission

- **Develop** and **mature** advanced ES technologies for transfer to vehicle platforms
- Test & evaluate ES technologies for prequalification and to **assess TRL (Technology Readiness Level)**.
- Identify **technology barriers** and develop technical solutions
- Be recognized as the team of experts in ES components and systems
- Provide technical support to customers, other teams and government agencies for all ES requirements
- Provide **cradle-to-grave** support for all Army ES systems



**The TARDEC Energy Storage Team is the single point of accountability to provide full service lifecycle engineering and integration support (cradle-to-grave) for Energy Storage systems for Army Ground vehicle platforms.**

- **TARDEC Energy Storage Team Role is the Engineering Support Activity (ESA) to ensure conformance with the specification & recommendation for QPL acceptance.**
- **TARDEC Standardization Team Role is the Qualifying Activity that maintains the modifications to the MIL-PRF 32143B and QPL.**

- ✓ First Article in-house Testing & Qualification Test Issues
- ✓ Develop, publish, and maintenance of battery standards and performance specifications
- ✓ Participate with DLA on audits of production facilities
- ✓ Establish vendor qualification criteria
- ✓ Provide technical expertise on energy storage systems for all stakeholders
- ✓ Project Management
- ✓ Preparing and updating Tech Manuals
- ✓ Provide SMEs for Analysis of Alternatives (AOAs)
- ✓ Provide sustainment and fielding support of batteries
- ✓ Research, develop, and mature advanced energy storage technologies for enhanced capability
- ✓ Establish and leverage collaborative projects, battery working groups, MOUs/MOAs with other government agencies



## Major Applications/Drivers

- Increased Electrical Power Draw
- Robotics
- Survivability
- Weapons Systems
- Electromagnetic Armor (EM Armor)
- Starting, Lighting and Ignition (SLI)
- Hybrid Vehicle Acceleration and Silent Mobility
- Silent Watch



Hit Avoidance



Targeting Systems



Communications



## Energy Storage Challenges:

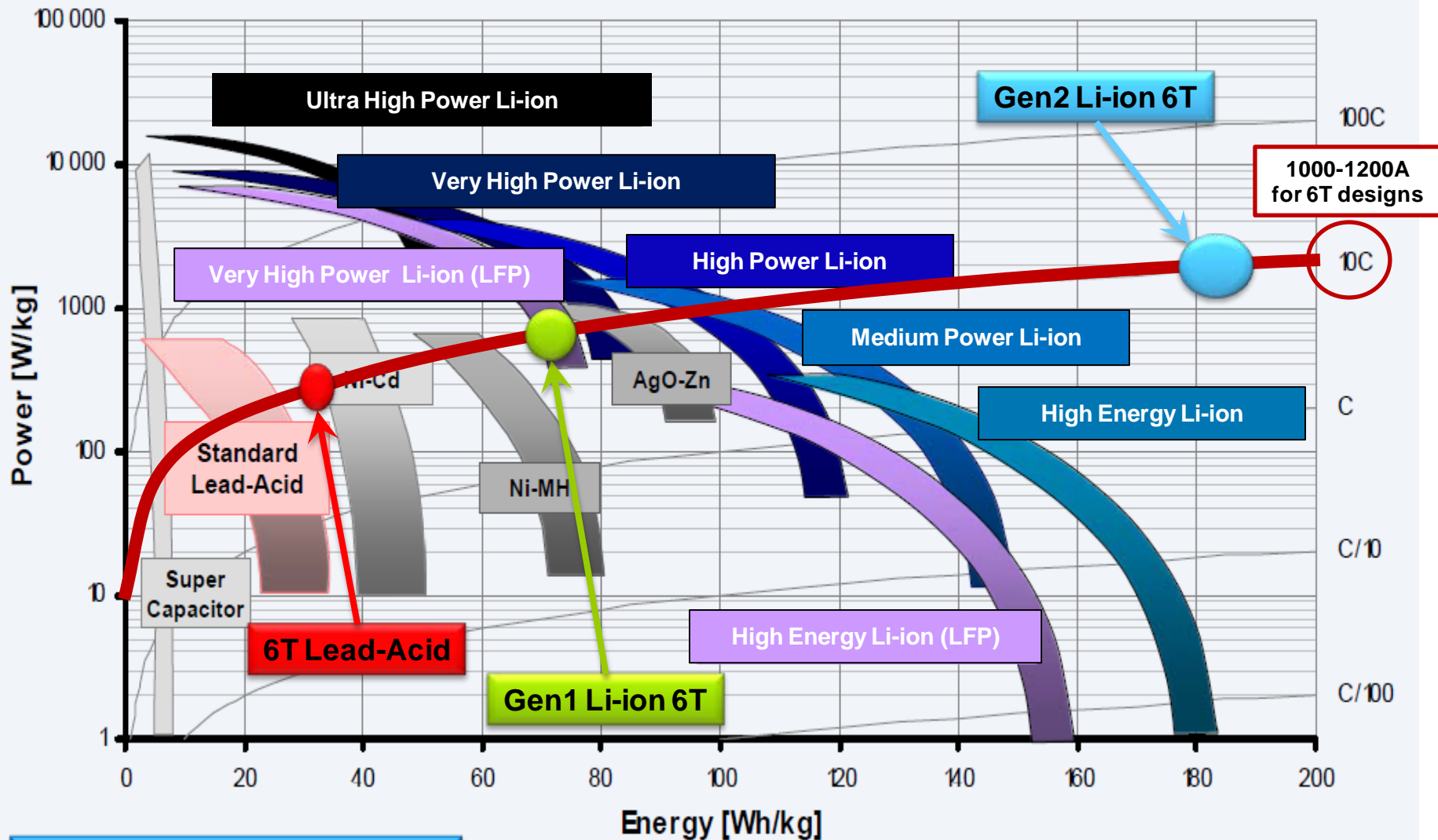
- Delivering reliable battery solutions in standardized military form factors (logistics/sustainability/compatibility)
- Safety – Understanding thermal runaway process and its control, improved BMS and alternative cell technologies.
- Developing energy storage systems with higher energy and higher power densities (focus on designs and chemistries).
- Manufacturing process development and quality (Reliability & Safety)
- Cost control (balancing \$ with ↑ performance & ↑ durability)
- Thermal Management

**Batteries represent one of the top ten ongoing maintenance costs in theater.**



- Current Lead acid battery: ~\$300/kWh
- Current Lithium ion battery: \$2000-\$5000/kWh
- Target price for Li-ion battery is \$500/kWh

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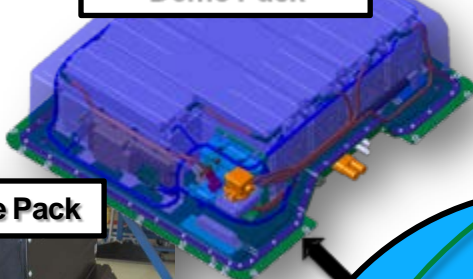


Where are we today...

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# Commercial vs. Military Energy Storage Requirements

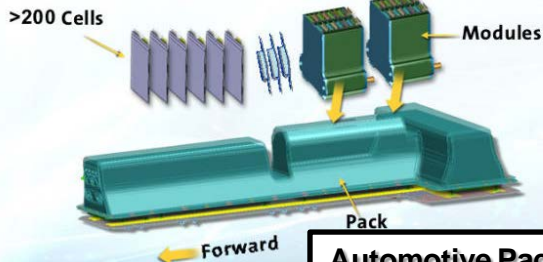
Heavy Duty Truck Demo Pack



Automotive Pack



Automotive Pack



Automotive Pack

*Divergence of Military and Commercial Requirements:*

## Commercial Focus

- Fuel Economy/Hybridized vehicles
- Increased energy – EV applications
- Increased power – HEV applications
- Cost (\$250/kWhr)
- Life (cycle/10-15 year calendar life)
- Safety
- SAE Standards
- Operation from to -20°C to +55°C

## Military Requirements:

- ✓ Operating Temperatures: **-46°C to 71°C**
- ✓ Storage Temperatures: **-54°C to 88°C**
- ✓ Electromagnetic Interference: MIL-STD-461F
- ✓ Ballistic Shock: MIL-STD-810G
- ✓ Life Fire: MIL-STD-810G
- ✓ Explosive Environment: MIL-STD-810G
- ✓ Altitude to 60,000ft: MIL-STD-29595
- ✓ Explosive Decompression: MIL-STD-810G
- ✓ Salt fog: MIL-STD-810G
- ✓ Sand and Dust requirements: MIL-STD-810G

## Additional Military Focus:

- ✓ NATO **Standardized** Form Factors (i.e. 6T)
- ✓ Maximized Power AND Energy density
- ✓ Sustainability and Logistics issues
- ✓ Silent Watch/Silent Mobility
- ✓ On-board Electric Power

Extreme operating environments

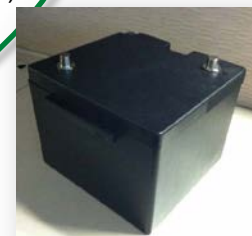


Commercial

Military



Standardized Military Batteries (i.e. 6T)  
Used in 95% of Military Vehicles



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## Accomplishments to date:

- Demo 2x increase in energy density
- Cut weight of each 6T in half (20kg vs. 40kg)
- Demo starting of HMMWV with single Gen1 24V battery (replacing 2 6TAGM)
- **Replaces 2 Lead Acid 6T batteries (@ 25% of weight!) 20kg (Li-ion) vs 80kg (Lead acid)**



**12V Lead-Acid  
6T Batteries**  
80kg total



**24V Li-ion 6T Battery**  
Replaces 2 lead acid 6Ts  
20kg

## Commercial Platforms



**Combat and Tactical Vehicles**



**Army Watercraft Systems (AWS)**



## Purpose and Products:

- The 6T battery form factor is currently utilized in ~95% of the military ground vehicle platforms, therefore improvements with this technology would have widespread implications.
- TARDEC has developed prototype Generation 1 24-V 6T form-factor Lithium ion (Li-ion) batteries (Gen 1 6T) from two different manufacturers. A third supplier is under development.
- Gen 1 6T batteries are designed to be backward compatible such that they can be used as a direct replacement for currently used lead acid systems. Additionally, Gen 1 6T batteries provide the following benefits: reduced weight, reduced volume (2 for 1 replacement 24V vs. 12V), reduced logistics & sustainment burden, increased cycle life, and advanced battery management with state of charge and state of health indicators.
- TARDEC is also demonstrating the standardized batteries in support of anti-idling and start/stop applications for commercial truck and vehicle applications – to leverage commercial volumes and reliability (reduce costs).

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Li-ion 6T  
Standardized  
Batteries



12V 6T Batteries

24V 6T Batteries



## PURPOSE AND PRODUCTS

- Leverage ongoing TARDEC investments/efforts to develop advanced Li-ion battery energy storage systems with improved energy and power density in standardized 6T form factors to develop dual use batteries in support of anti-idling and start/stop applications for commercial truck and vehicle applications.
- Products:
  - Advanced 6T size 12V and 24V Li-ion battery systems with improved power and energy densities capable of operation at extreme temperatures.
  - Commercial based passenger and truck demonstration vehicles to establish dual use capability of the standardized military batteries in support of anti-idling and start/stop applications.

CALSTART POC: Jasna Tomic

## SCHEDULE AND COST

MILESTONES	FY12	FY13	FY14
Applied Research	4		6
6T Li-ion 12V & 24V Battery Dev		4	6
Development of Demonstration Vehicles			TRL
Demonstration/Gov't Test			

## ARMY/DOE BENEFITS

- Dual Benefit:** By leveraging military investment, a versatile battery system would be developed providing a significant improvement in overall capability for military and commercial applications. Furthermore, by developing commercial market overall systems costs would be reduced.
- DA Benefit:** Development of standardized form factor battery systems with maximized power and energy density would enable a single battery system that could meet both energy requirements as well as pulse power requirements while reducing the logistic footprint.
- DOE Benefit:** With minimal investment, DOE will leverage standardized batteries in support of anti-idling and start/stop applications for commercial truck and vehicle applications.

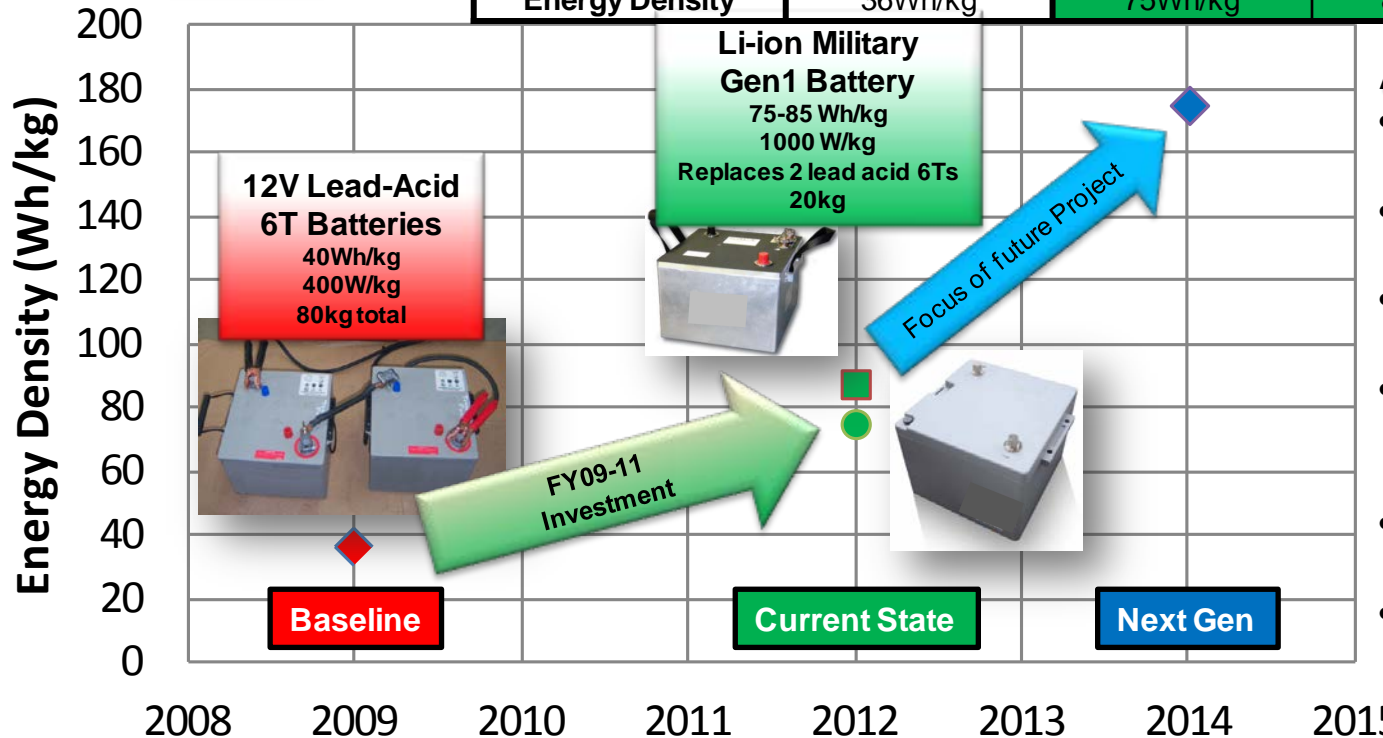
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# Li-ion 6T Development (5-10 years)

Standardized Military Batteries (i.e. 6T)  
Used in 95% of Military Vehicles



	Baseline 6T Lead acid	Generation 1 Li-ion 6T		Generation 2 Li-ion 6T
		Vendor A	Vendor B	
Voltage	12V	24V	24V	24V
Capacity (rate)	120Ahr (C/20)	60Ahr (C-rate)	70Ahr (C-rate)	120Ahr (C-rate)
Peak Current (-19C, 30sec)	1100A	>900A	1100A	1400A
Deep Cycle Life (100% DOD)	120	500-1000	500-1000	>1000
Weight	40kg	20kg	20kg	20 kg
Energy Density	36Wh/kg	75Wh/kg	88Wh/kg	150-170Whr/kg

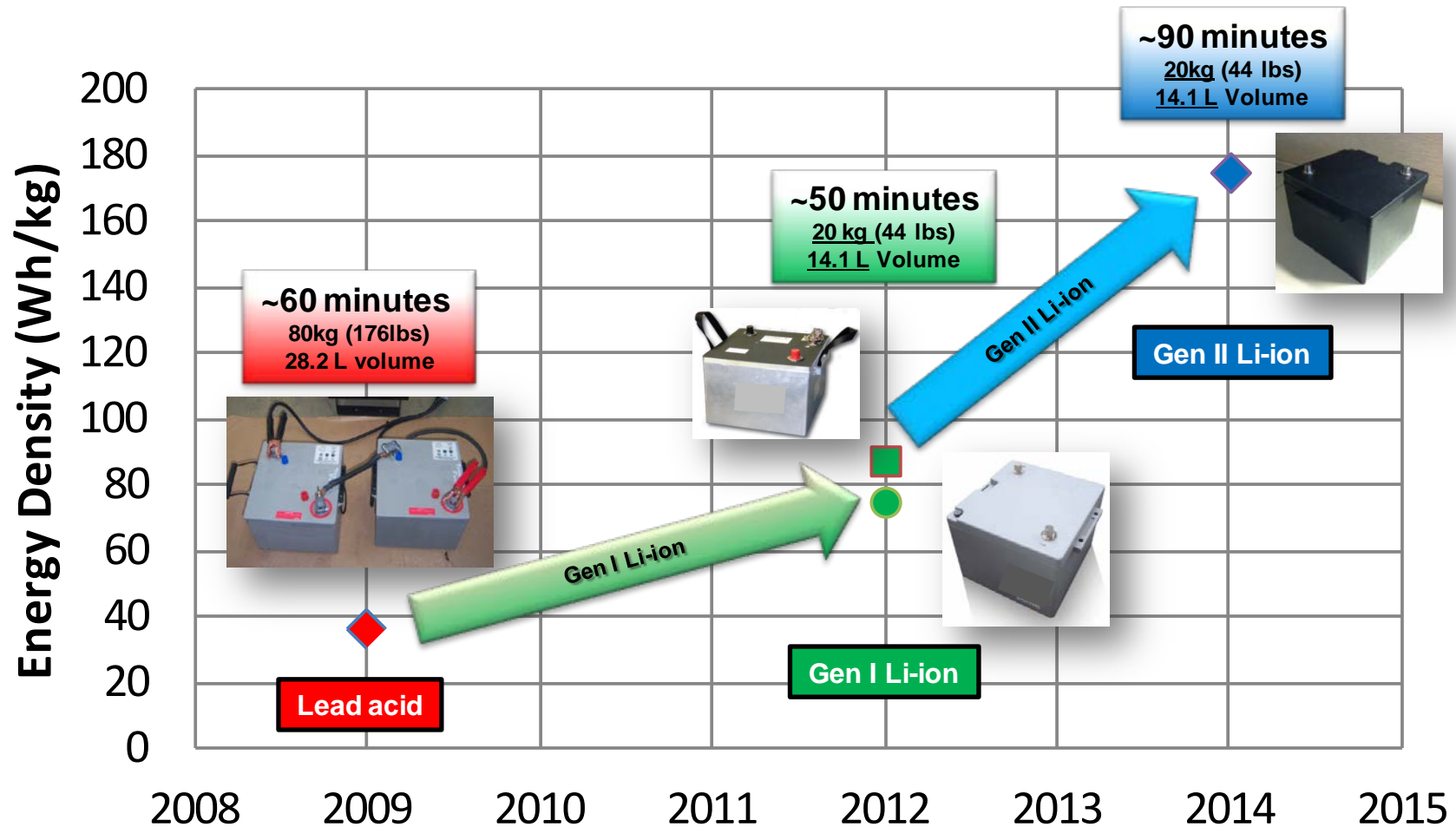


## Accomplishments to date:

- Developed Gen1 Li-ion 6T batteries
- Demo 2x increase in energy density
- Cut weight of 6T in half (20kg vs. 40kg)
- Demo starting of HMMWV with single Gen1 24V battery (replaces 2 LA 6T!)
- Gen1 TRL 5/6 testing underway.
- Gen1 batteries to be field tested.

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Assume a continuous silent watch load of 2kW...



Battery Suppliers	Hot/Mountain Region	Cold/Mountain Region
Navitas	Fleet Location: 7250 North Cajon Blvd San Bernardino, CA	Fleet Location: 9351 Willow Ct Henderson, CO
Saft America		
EaglePicher		



2007 Kenworth T800B  
(battery box cover removed)



### The following requirements were used for truck selection:

- Trucks should drive a minimum of 20,000 miles per year.
- Li-ion batteries need to fit in the existing 12V battery compartment.
- Li-ion batteries need to be compatible with the existing alternator system
- Truck electrical load requirements shall not exceed 18 kW at any given time.

### Additional guidelines for truck selection:

- Trucks should be Class 8 truck tractors (GVWR > 33,001 lbs.).
- Trucks daily operation should include long-haul and/or city pickup and delivery shifts.
- Double shift (Day and Night) preferred
- Trucks should operate a significant portion of time at idle (vehicle speed equals to zero with engine on).

### Current Status:

- Trucks and regions selected
- 12V and 24V 6T Li-ion batteries have been ordered.
- Test Plan developed

## Vehicle Parameters to be monitored:

- Operating hours
- Speed
- Number of key on/off events
- Mileages driven
- An outline of vehicle operation profile
- Hotel electrical loads during engine idle (case by case and average)
- Total Idle hours
- Total energy throughput of batteries (Whr)
- Ambient air temperature as a function of time - frequency of one measurement/30mins
- Hotel loads (if any) as a function of time - frequency of one/min
- Alternator current as a function of time in frequency of one/min
- Current as a function of time in frequency of one/5sec
- Voltage as a function of time in frequency of one/5sec
- Battery temperatures ranges as a function of time in frequency of one/15mins
- SOC as a function of time in frequency of one/min





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## Back-up Info

## 35°C Cycle Life Analysis

**1C/1C Li-ion Cycle Life**  
**100% Depth of discharge**  
**{100% SOC to 0% SOC}**  
Discharge: 1 hour @ 1C (60A)  
Charge: 1 hour @ 1C (60A)  
**Total time/cycle = ~2 hours/cycle**

Li-ion cell data

**Li-ion allows for a  
more aggressive  
durability profile**

24V Li-ion 6T Battery

12V 6T AGM Lead Acid

Cells utilized for 6T Li-ion packs....

Cycle life >1000 cycles at  $\pm 5C$  observed for some cells.

2500+ Cycles

Expectation...  
Gen 1

>1000 Cycles

Currently evaluating  
Li-ion 6T Cycle Life

Current Lead Acid  
~120-150 Cycles



0 500 1000 1500 2000 2500

**100% DOD Cycles**

**Lead Acid Deep Cycle Test**  
(per MIL-PRF-32143B)  
Discharge: 1 hour @ 40A followed  
by 15A discharge to voltage limit.  
Charge: At 14.7V for 10 hours (or current = 0.15A)  
**Total time/cycle = ~10 to 16 hours/cycle**

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		6T	Group 31	Group 34	4HN	6T Lead Acid
Voltage (V)		26	13	13	26	12
Capacity (Ahr)		100	150	100	50	120
Battery Size	volume (L)	14.1	11.4	9.0	7.3	14.1
	length (mm)	265	330	260	260	265
	width (mm)	255	173	173	135	255
	height (mm)	208	200	200	208	208
Physical Dimensions, Terminal and Handle Specifications		MIL-PRF-32143A	BCI Battery Replacement Book	BCI Battery Replacement Book	MIL-B-11188H	MIL-PRF-32143A



- Li-ion battery has to work with existing vehicle electrical system
- Li-ion battery is sensitive to the battery overcharge
- Li-ion battery is sensitive to the battery overdischarge



# of Cells	1	3	4	6	7	8	n
Nominal Voltage(V)	3.7	11.1	14.8	22.2	25.9	29.6	n x 3.7
Voltage range (V) (NCA, NCM)	2.5-4.1	7.5-12.3	10-16.4	15-24.6	17.5-28.7	20-32.8	
Nominal Voltage(V) (LiFePO <sub>4</sub> )	3.3	9.9	13.2	19.8	23.1	26.4	n x 3.3
Voltage range (V) (LiFePO <sub>4</sub> )	2.0-3.7	6-11.1	8-14.8	12-22.2	14-25.9	16-29.6	

**Battery voltage**

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## Capabilities

- Provides steady state and transient (mission profile based) testing
- Ability to test current and emerging classes of ground vehicles
- 32,000 ft<sup>2</sup> of laboratory space
- Environmental chamber able to test between -60° to 160° F with winds up to 60 mph
- Provides 10 dynamometers to allow testing of up to 5 axle wheeled vehicles



Grand Opening pril 11, 2012

Certified Leadership in Energy and Environmental Design (LEED) Silver  
in accordance with the US Green Building Council (USGBC)

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## Purpose:

The GSPEL Energy Storage Lab is TARDEC's testing laboratory and will be used to safely analyze, evaluate and test battery and other electrochemical technologies at the cell, module level, and pack level.

## Capabilities:

- Characterize and evaluate advanced technologies (lithium-ion, nickel-zinc, lead acid, ultra capacitors families, and any future new chemistry that is developed)
- Centrally controlled and monitored cyler circuits of varying current and voltage capabilities
- Characterization at different charge/discharge rates/temperatures/life cycling/pulse power/stand testing/& drive profile cycling
- Temperature test ranging from -73°C to 200°C.
- Lead acid batteries battery life analysis



## Equipment:

- 3 blast proof rooms
- 2 pack external battery pack test chambers
- ~100 cell level cyler channels
- ~100 (0-60V) module/pack level cyler channels
- 6 pack test cyler channels (AV900)
- 12 environmental chambers
- 6 water baths for testing Pb Acid batteries
- Accelerated rate calorimeter

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### Safety Features:

- The rooms are designed to withstand 25 psi
- Room and doors are designed to withstand this pressure and actually hold it for a controlled release.
- Walls are ~8 inches thick concrete and are re-enforced with tie rods.
- 100% air is replaced 8 times per hour. In emergency, air changes increase to 24 per hour.
- All air is passed thru a scrubber located on the roof.
- Sensors include heat, smoke, hydrogen, and organic vapors
- Fire suppression includes - Nitrogen/Argon gas fire suppression, water sprinkler system, and capability to flood the room
- E stops located in the control room, test chamber, and outside the rooms shut down all electrical equipment operating in the room and feeding the room from the mezzanine.
- Spill containment is located under the floor to contain and control spills.



## Purpose:

The EARL is TARDEC's testing laboratory for analyzing and evaluating battery and other electrochemical technology at the cell & module level. Testing in this laboratory aids TARDEC in understanding new breakthrough technologies for Army ground vehicle energy storage systems.

## Capabilities:

EARL contains a number of battery cyclers for charging and discharging batteries, along with thermal chambers and a centralized control system that enables assessment of electrochemical cells with a variety of tests including:

- Characterization at different charge/discharge rates and temperatures
- Life cycling
- Hybrid pulse power characterization
- Stand testing
- Tests are monitored with thermocouples and video feed

## Equipment:

Three Battery Cyclers

- 16 & 4 Channel Bitrode, 4 Channel Maccor
- Two Solartron SI 1287 Electrochemical Impedance Spectrometers
- Parstat 2273 Potentiostat
- Walk-in Hood with 4 chamber fire suppression system
- Three Tenny thermal chambers
- Centralized Control System



**Battery Cycling  
Equipment**



**Thermal Chambers & Exhaust Hood**



**Electrochemical  
Characterization**

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### Purpose:

The Battery Management System (BMS) laboratory is TARDEC's Lab for analyzing and evaluating prototype, near production ready, and commercial-off-the-shelf BMS units for lead acid and Li-ion batteries. BMS evaluation in this lab supports the PM/PEO to determine if the system is ready for fielding. Testing also aids TARDEC in updating the BMS specification that is used by the customer for battery management qualifications that will be used in fielded vehicles.

### Capabilities:

The BMS lab contains

- BMS Hardware-In-the-Loop (HIL) which can simulate a battery profile
- Thermal chambers
- Analog and digital input/output (I/O)
- Centralized control system



**Hardware-in-the-loop  
(HIL) Battery Simulator**



**Thermal chambers**

### Equipment Specification:

- BMS HIL – Independently simulate and control up to 180 cells from 0 to 5 volts.
- Pack voltages up to 750V can be simulated.
- Large Thermal Chamber – 8 cubic feet, remotely programmable from -73°C to 200°C.
- Two Small Thermal Chambers – 1 cubic foot, remotely programmable from -73°C to 200°C.
- Independent Data Acquisition (I/O)
  - 16 channels of digital input
  - 16 channels of digital output
  - 16 channels of analog input
  - 16 channels of analog output
  - 16 channels of thermocouple
- Centralized Control System – control all lab equipment



**Centralized data  
acquisition & control  
system**